



## The Influence of Frequency on Route Choice in Mixed Schedule- and Frequency-based Public Transport Systems - The Case of the Greater Copenhagen Area

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## **The influence of frequency on route choice in mixed schedule- and frequency-based public transport systems – The case of the Greater Copenhagen Area**

**Morten Eltvéd · Otto Anker Nielsen · Thomas Kjær Rasmussen**

### **Abstract**

Understanding and analysing passengers' route choice preferences is critical to realistically predict the level of service for the passengers', when timetables change or new infrastructure is build. This paper argues and presents evidence on the influence of frequency of public transport services and whether published timetables are schedule- or frequency-based when describing passengers' route choice in mixed schedule- and frequency-based public transport systems. The study is based on a revealed preference survey with 5,121 reported trips in the Greater Copenhagen Area. Given the observed trips and a corresponding large choice set with alternative routes, passenger preferences are revealed using the well-known Multinomial Logit model.

Utilising recently published research on how passengers time their arrival to the first stop, the paper shows how to estimate passengers' preferences for avoiding waiting at the first stop. The analysis also shows that passengers prefer high frequency routes. This is shown by considering the highest headway in any leg of a trip, as well as by introducing a variable capturing passengers' higher preference for frequency-based compared to schedule-based services. On the other hand it is shown, that passengers prefer waiting for a schedule-based service compared to a frequency-based service when transferring, implying that passengers want to be certain about the time they need to wait when transferring. Finally, the paper examines the transformation of the in-vehicle time components according to a Box-Cox transformation, and highlights the varying trade-offs between in-vehicle times of different vehicles at different travel time levels.

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## 1 Introduction

The public transport system in most metropolitan areas, including the Greater Copenhagen Area, is a mix of high and low frequency services where the published timetable for some lines is schedule-based (SB), while being frequency-based (FB) for others. The passengers are therefore often in a situation where the route choice includes options where both SB and FB services are viable alternatives relevant to consider. The combination of the two types of services, independent of public transport mode, leads to a more complex route choice, where the frequency of services are important for various reasons, e.g. in relation to transfers.

In the literature, the utility function of passenger's route choice primarily includes the quantifiable time components (in-vehicle, access/egress time, waiting time at transfers and walking time), a transfer penalty and in relevant cases the ticket price (Gentile and Noekel, 2016, chap. 4). Some applications also include the other factors such as in-vehicle crowding, level changes at transfers and other attributes at transfer stations as well as topological characteristics for the spatial dimension of a trip (Raveau et al., 2014). Implicitly, the impact of frequency on route choice has typically been captured by the hidden waiting time and waiting time in a linear way. However, as it was shown in Anderson et al. (2014) the inclusion of headway of the trip proved to provide a significantly better model fit.

This paper utilises a large disaggregate dataset of observed behaviour in the Greater Copenhagen Area. The results demonstrate, that the model fit to observed behaviour can be improved further by (i) separating waiting for SB and FB services at transfers; (ii) using new knowledge identified in (Ingvardson et al., 2018) about passengers' waiting time at the first station to enrich the detailed dataset; (iii) relating passengers' route choice to the published timetables to identify preferences for FB and SB services by including a dummy for FB services; and (iv) analysing trade-offs between in-vehicle times at different travel time levels.

The paper is structured as follows; Section 2 introduces the dataset used in the study and the methodology for estimating passenger preferences, Section 3 presents the results, followed by a discussion and conclusion of the study in section 4.

## 2 Data foundation and methodology

The dataset used in this study consists of 5,121 observed routes made by public transport in the Greater Copenhagen Area. The data were collected in the years 2009-2011 as part of the Danish National Transport Survey (Center for Transport Analytics DTU, 2017). The observed routes were matched to a SB representation of the public transport network as described in Anderson and Rasmussen (2010). A choice set of alternatives corresponding to each observed route was generated using a simulation-based choice set generation method described in Rasmussen et al. (2016). The final choice sets consist of between 18-200 alternatives for each observation with an average of 128 unique alternatives per observed route.

### 2.1 Description of network

The public transport network in the Greater Copenhagen Area is a mix of SB and FB services. The FB services are found in the most densely populated areas of Copenhagen, consisting primarily of the metro operating with a headway of 2-4 minutes during peak hour, and the "A-buses" (high frequency buses), with headways between 3-8 minutes during peak hours. All other buses, regional trains and suburban trains (S-tog) in the Greater Copenhagen Area operate with published schedules with headways between 5-90 minutes. The figures below show examples of the published timetable for a FB and a SB bus line. In particular, note in the case of line 3A and 150S, the SB bus line 150S runs with a higher frequency than the bus line 3A.

3A									150S										
	Nordhavn st.	Triangeln	Elmegade	Åboulevard	Vesterbrogade	Enghave st. (Ligstavevej)	Sydhavn st.	Kgs. Enghave (Rådhuspladsen)		Køkkedal St.	Fredensborg Rådhus	Botbrovej	Hovedgaden	Gl. Høtte (Højsholmvej)	Nørre St.	Klampenborgvej	Ryparken St.	Hans Knudsen Plads	Nørreport St.
mandag - fredag	4.50	4.55	5.00	5.03	5.09	5.13	5.15	5.21	5.25	5.30	5.33	5.37	—	5.48	5.54	6.04	6.05	6.14	6.14
	5.10	5.15	5.20	5.23	5.29	5.33	5.35	5.41	5.46	5.51	5.54	5.58	—	6.09	6.15	6.25	6.26	6.36	6.36
	5.30	5.35	5.40	5.43	5.49	5.53	5.55	6.01	6.04	6.09	6.12	6.16	—	6.27	6.33	6.43	6.44	6.54	6.54
	5.40	5.45	5.50	5.53	5.59	6.03	6.05	6.11	6.14	6.19	6.22	6.26	—	6.37	6.43	6.53	6.54	7.05	7.05
	5.50	5.55	6.00	6.03	6.09	6.13	6.15	6.21	6.24	6.29	6.32	6.36	—	6.47	6.53	7.03	7.04	7.15	7.15
	6.00	6.05	6.10	6.13	6.19	6.23	6.25	6.31	6.33	6.38	6.41	6.45	—	6.57	7.03	7.14	7.15	7.26	7.26
	6.09	6.14	6.19	6.22	6.28	6.32	6.34	6.40	—	—	—	—	—	7.06	7.11	7.22	7.23	7.35	7.35
	6.19	6.24	6.29	6.32	6.38	6.42	6.44	6.50	6.45	6.50	6.53	6.58	—	7.10	7.16	7.27	7.28	7.40	7.40
	6.28	6.33	6.39	6.42	6.48	6.52	6.54	7.00	6.55	7.00	7.03	7.08	—	7.21	7.27	7.38	7.39	7.51	7.51
	6.36	6.42	6.48	6.51	6.57	7.01	7.03	7.10	7.06	7.11	7.14	7.19	—	7.26	7.32	7.43	7.44	7.56	7.56
	6.44	6.51	6.57	7.00	7.07	7.11	7.13	7.20	7.05	7.11	7.14	7.19	—	7.32	7.38	7.50	7.51	8.03	8.03
	6.52	6.59	7.05	7.09	7.16	7.20	7.22	7.29	7.15	7.21	7.24	7.29	—	7.37	7.43	7.55	7.56	8.08	8.08
									7.15	7.21	7.24	7.29	—	7.43	7.49	8.01	8.02	8.14	8.14
									7.25	7.31	7.34	7.39	—	7.49	7.55	8.07	8.08	8.20	8.20
									7.35	7.41	7.44	7.49	—	7.55	8.01	8.13	8.14	8.26	8.26
									7.45	7.51	7.54	7.59	—	8.00	8.06	8.18	8.19	8.31	8.31
									7.55	8.01	8.04	8.09	—	8.05	8.11	8.23	8.24	8.36	8.36
													—	8.10	8.16	8.28	8.29	8.41	8.41
													—	8.15	8.21	8.33	8.34	8.46	8.46
													—	8.20	8.26	8.38	8.39	8.51	8.51
													—	8.25	8.31	8.42	8.43	8.55	8.55
													—	8.32	8.38	8.49	8.50	9.02	9.02

Figure 1 - Example of a frequency-based bus (3A between 7am-5pm) and a schedule-based service (150S) (Movia, 2011)

Figure 2 gives an overview of the public transport system in the Greater Copenhagen Area, when dividing the network into SB (rail and most busses) and FB lines (metro and some busses) respectively. The map clearly shows the concentration of FB services in the central part of Copenhagen.

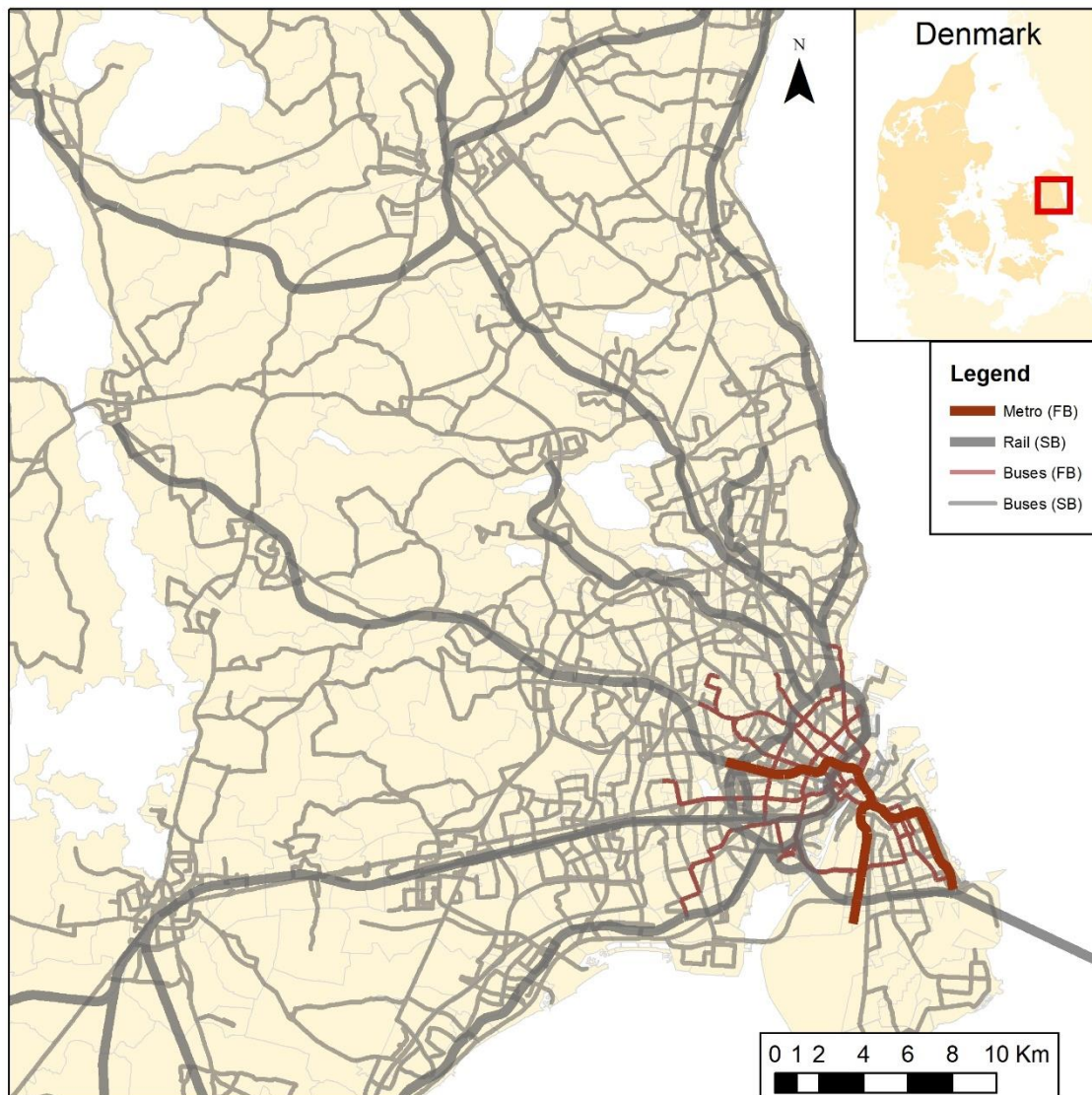


Figure 2 - Schedule-based (SB) and frequency-based (FB) services in the Greater Copenhagen Area

## 2.2 Observed routes

The observed routes are distributed across the whole case-study area, and have a large variation in terms of the components (Table 1). All variables have large standard deviations, which for most of the variables, e.g. sub mode specific in-vehicle times and waiting time at transfers, is due to the many routes which have not used a specific sub mode or made any transfers, i.e. not having any waiting times at transfers. The most used sub modes in the data are buses and S-trains which are also the primary services covering the case-study area.

All variables, except the headway variables and waiting time at the first stop, are directly extracted from the matched observed routes. The headway of each leg in the trip is found by the minimum amount of the time to the previous and next departure (run) of the same line between the same stops. The highest headway of the trip is defined as the highest headway of the legs in the trip.

Table 1 - Trip characteristics for observed routes

<b>Trip component</b>	<b>Mean</b>	<b>Std. dev.</b>
<b>Total travel time</b>	36.47	20.82
<b>In-vehicle time total</b>	20.21	13.76
<b>In-vehicle time bus</b>	8.25	11.08
<b>In-vehicle time SB bus</b>	6.14	10.33
<b>In-vehicle time FB bus</b>	2.11	5.91
<b>In-vehicle time metro</b>	1.39	3.56
<b>In-vehicle time S-train</b>	7.44	11.18
<b>In-vehicle time local train</b>	0.60	4.00
<b>In-vehicle time regional train</b>	2.53	8.43
<b>Nb. of transfers</b>	0.48	0.64
<b>Waiting time at transfers</b>	2.52	6.10
<b>Waiting time at first stop</b>	3.85	2.64
<b>Walking time</b>	0.97	1.58
<b>Access/egress</b>	12.78	9.36
<b>Headway of first leg</b>	11.88	16.29
<b>Highest headway in trip</b>	14.32	17.42
<b>Include frequency-based service (dummy)</b>	0.34	0.47
<b>Total number of observations</b>	5,121	

The waiting time at first stop is derived from the headway of the first leg, and whether the first leg is a SB or FB service. The distinction between SB and FB services is made because a recent study from Ingvardson et al. (2018) showed that passengers who know the exact planned departure time of a run come partially planned to the first stop thereby minimizing the waiting time at the first stop. The study by Ingvardson et al. (2018) only covered rail services, but the assumption of this present work is that the calculated waiting times also applies for bus services. The waiting time at the first stop for FB services is given by half of the headway, as passengers are assumed to arrive completely random to these services, which was also shown to be true in the study. For SB services the passengers arrive more timed the longer the headway is as shown in Figure 3. The waiting time at the first stop ( $F$ ) increases with the headway, and is found by the following formula:

$$F = \begin{cases} 0.5 * H & \text{if } L = FB \\ 0.5181 * \exp(H) * H & \text{if } L = SB \end{cases}$$

, where  $L$  is the first leg in the trip and  $H$  is the headway of the first leg in the trip.

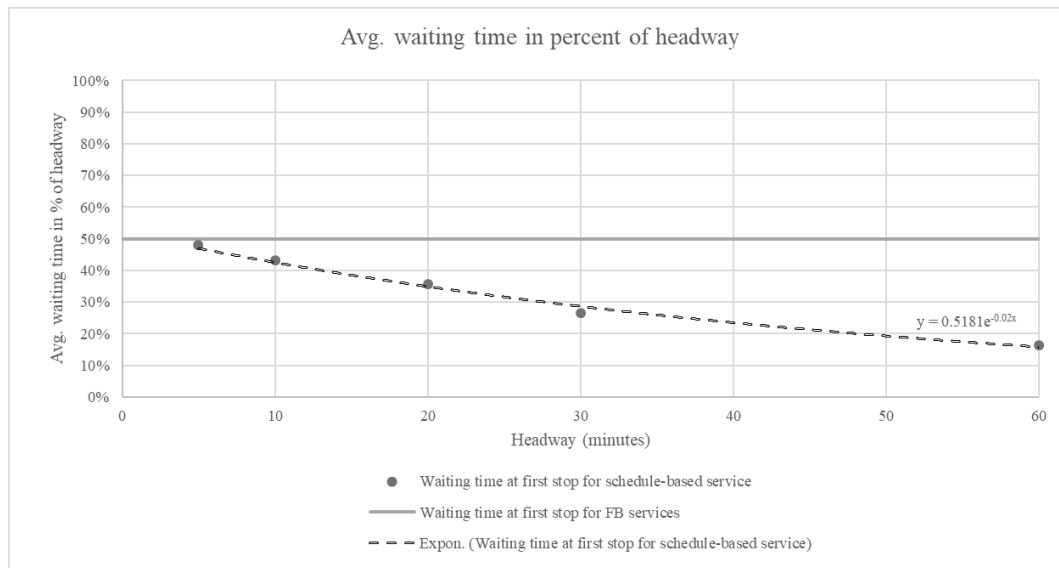


Figure 3 -Average waiting time at first stop in percent of headway for respectively SB and FB services

Figure 4 illustrates the total travel time and in-vehicle time for the observed trips. As seen in the cumulative distribution function for the total travel time, the dataset include a wide range of travel times, with most observations having around 20 to 40 minutes total travel time. Around 15% of the 5,121 trips last for more than one hour, and 27 observed routes have a travel time exceeding two hours. The total in-vehicle time varies between very short trips with only a few minutes of in-vehicle time to in-vehicle times of more than an hour. Most trips include between 15-30 minutes in-vehicle time, which is also reflected in the total travel time for most trips being 20-40 minutes.

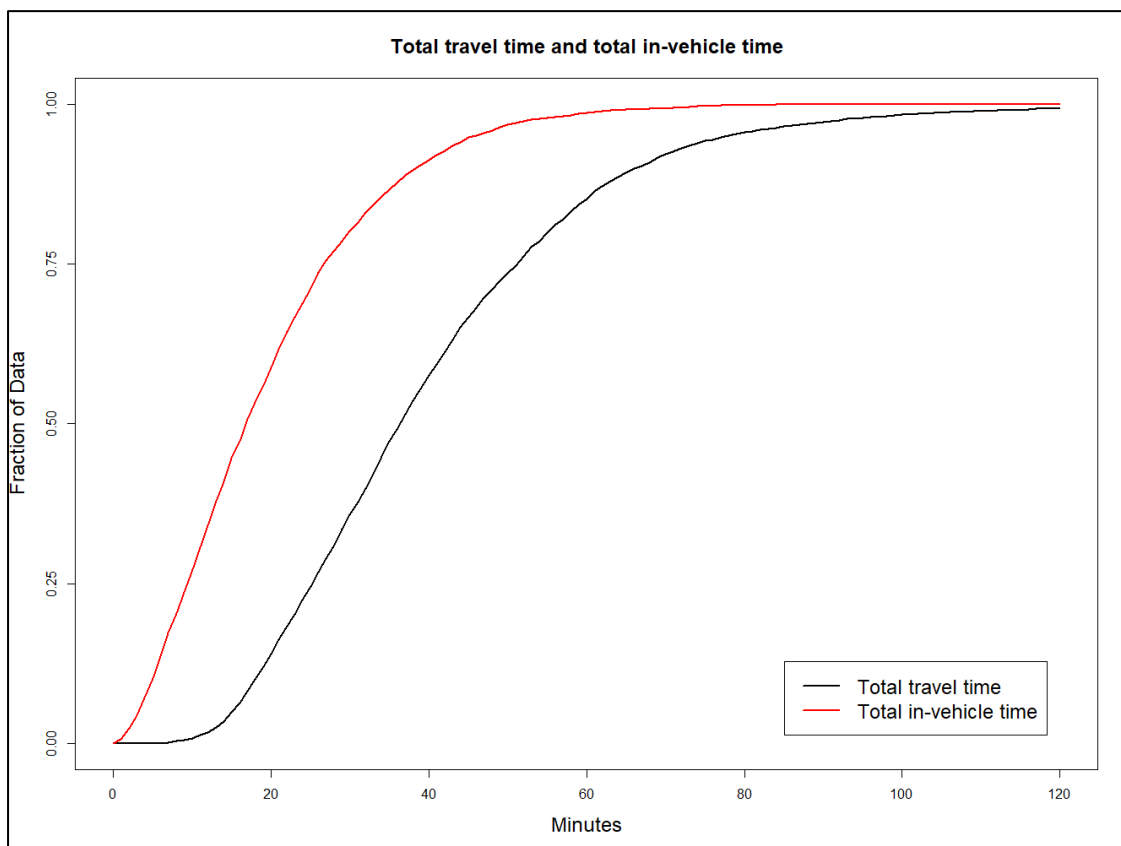


Figure 4 - Cumulative distribution function for total travel time and total in-vehicle time for observed trips. (27 observations have a total travel time higher than 120 minutes – max 232 minutes)

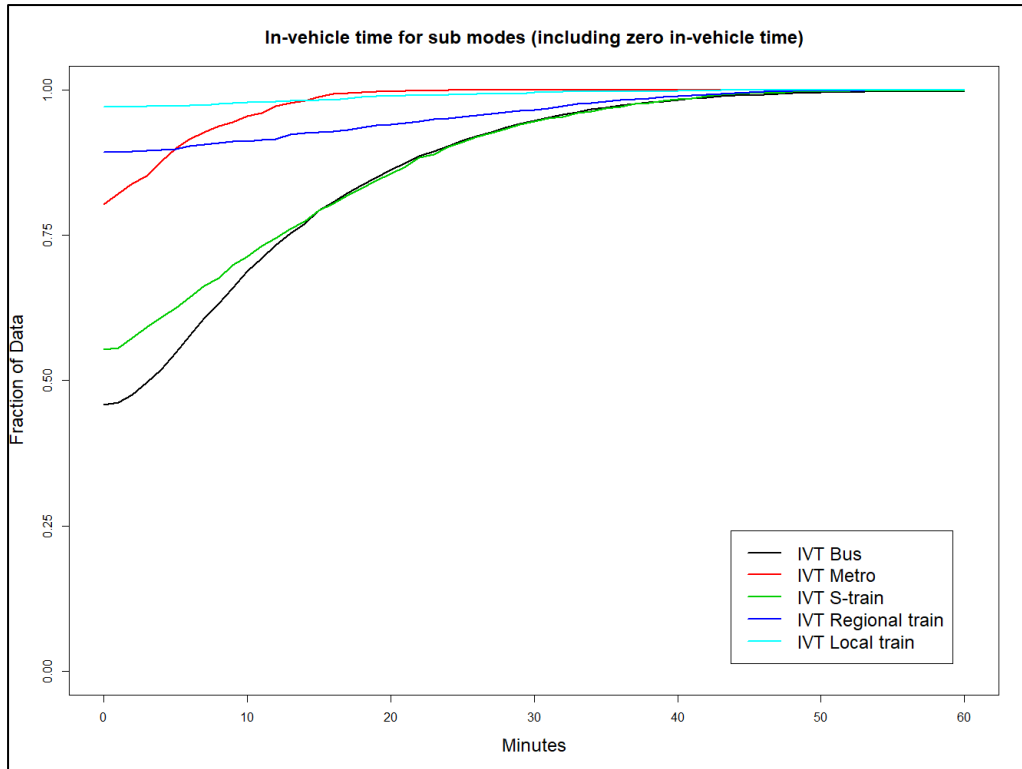


Figure 5 -Cumulative distribution functions of sub mode in-vehicle times of observed trips including trips that did not use the specific sub mode (zeros)

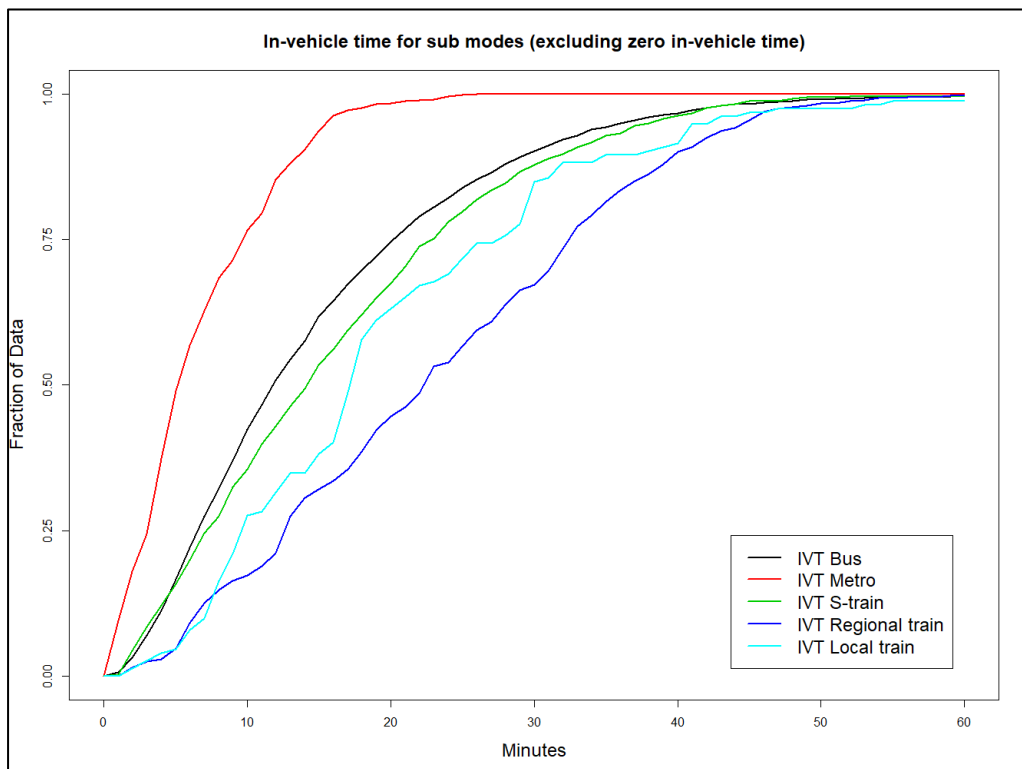


Figure 6 - Cumulative distribution functions for in-vehicle times of observed trips excluding trips that did not use the specific sub mode (zeros).  
Few observations for local train result in a less smooth curve than for other sub modes.

Figure 5 and Figure 6 illustrate the distribution of the different variables related to the in-vehicle times of sub modes of the observed routes. Figure 5 shows the distributions when also including trips where the passenger did not use the specific sub mode, while Figure 6 shows the distributions only including trips where passengers used the sub mode. More than 50% of the trips use a bus and almost half of the trips use the S-trains, while only around 20% use the metro, and the regional and local trains are used even less frequently than the metro. When removing all trips not including a specific sub mode, the plots in Figure 6 shows a wide range of in-vehicle times for S-train, buses and regional train, while the in-vehicle times for metro use is significantly shorter. This is due to shorter lines which serve more trips centred in the inner areas of Copenhagen, which would be expected to have shorter trips.

Figure 7 shows the cumulative distribution for the other component of the trips. The access/egress times varies between a few minutes and 30 minutes, where the waiting times at the first stop is centred from two to five minutes. The walking and waiting times at stops is proportional to the number of transfers in the trips, where more than half of the trips are single legged. The final variable is the highest headway of the trip, where most trips have headways of 10 minutes or below, while few have headways higher than thirty minutes.

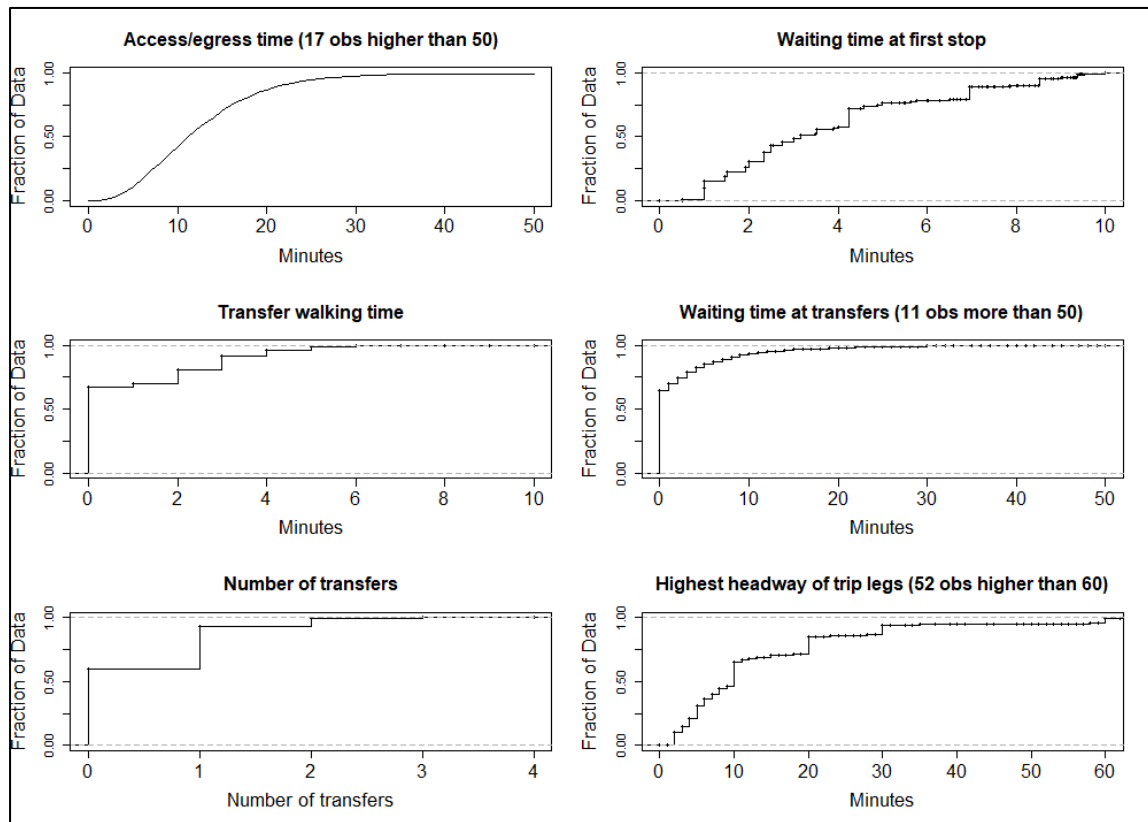


Figure 7 - Cumulative distribution functions for trip components other than IVT of observed trips

### 2.3 Methodology

Various multinomial logit models are estimated to reveal the route choice preferences of travellers (Train, 2002). The utility  $U_{kn}$  of an alternative  $k$  in the choice set  $C_n$  for each observed route  $n$  is described with the following utility specification:

$$U_{kn} = V_{kn} + \epsilon_{kn} \quad \forall K \in C_n$$

, where,  $V_{kn}$  is the deterministic part of the utility and  $\epsilon_{kn}$  is the random utility assumed to be gumbel distributed.



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The deterministic part of the utility  $V_{kn}$  is specified as:

$$V_{kn} = \sum_m \beta_{IVT,m} IVT_{mkn} + \sum_c \beta_{t,c} t_{ckn} + \sum_q \beta_{y,q} y_{qkn}$$

, where  $IVT_{mkn}$  is the in-vehicle time for component  $m$ ,  $t_{ckn}$  is the time component  $c$  not related to in-vehicle time (e.g., waiting, walking, access/egress and headway) and  $y_{qkn}$  is component  $q$  not related to time (e.g., transfer penalties and dummy variable for trips including FB services). The choice probability of route  $k$  for observation  $n$  is given as:

$$P_{kn} = \frac{\exp(V_{kn})}{\sum_{l \in C_n} \exp(V_{ln})}$$

The estimations made in the analysis for this paper build on the work made in Anderson et al. (2014), but exclude the path size correction factor, as the factor proved not to be significant when adding multiple new variables. The focus of the estimation procedure was to test the hypothesis concerning waiting time preference when transferring to either a SB or FB service; estimating first waiting time correctly; check for passenger preferences by including a dummy variable for trips including a FB service; and finally to estimate Box-Cox transformations for in-vehicle times. The Box-Cox transformations estimated follow the formula given below:

$$x(\lambda) = \frac{x^\lambda - 1}{\lambda}$$

where  $\lambda$  is the transformation parameter to be estimated (Box and Cox, 1964), and  $x$  is the variable, which is transformed.

### 3 Results

This section presents the results of estimations of models including different variables, which describe passengers' route choice preferences in the Greater Copenhagen Area. In total more than 100 different specifications were tested to achieve the best model fit. This section presents the base model followed by the elaborate model; including the waiting time at first stop, highest headway of trip, split between waiting for SB and FB services, and dummy for whether the route includes a FB service.

#### 3.1 Base specification

Table 2 show the estimates of the base specification including the variables access/egress, in-vehicle time of the sub modes, waiting times at transfers, walking time at transfers and transfer penalty. The results show that passengers prefer S-train, local trains and, especially metro compared to bus and regional trains. The higher disutility of regional trains compared to bus use is not as expected, but could be a result of few good viable alternatives to trips using regional trains, because there are typically no other services running in the same corridors as the trains. The access and egress time is, as expected a higher disutility than being inside a vehicle.

From the model it appears that walking and waiting time at transfers is preferred compared to in-vehicle time, but this is due to the transfer penalty, and it is therefore important to note that waiting and walking time at transfers have to be seen in the context of the high transfer penalty. The transfer penalty is equivalent to approximately 9 minutes of in-vehicle time in bus, but is lower for work related trips and higher for leisure trips. For work trips this could be due to passengers primarily trying to minimize the total travel time, while leisure trips avoid transfers to a higher extent possibly because they are not as familiar with the transfer options and the certainty of reaching a connecting service.

Table 2 - Estimates (robust t-test) for model with base specification and rates of substitution scaled to bus in-vehicle time

	Model estimates			Rates of substitution (to bus IVT)		
	Trip purpose			Trip purpose		
Parameter	All	Work	Leisure	All	Work	Leisure
<b>In-vehicle times</b>						
Bus	-0.190 (-32.84)	-0.216 (-26.47)	-0.163 (-21.61)	1.00	1.00	1.00
Metro	-0.066 (-7.37)	-0.086 (-6.54)	-0.044 (-3.74)	0.35	0.40	0.27
S-train	-0.146 (-22.46)	-0.170 (-17.23)	-0.117 (-14.60)	0.77	0.79	0.72
Regional train	-0.200 (-20.57)	-0.215 (-16.61)	-0.183 (-10.87)	1.05	1.00	1.12
Local train	-0.150 (-9.63)	-0.189 (-8.80)	-0.117 (-4.50)	0.79	0.88	0.72
<b>Other time components</b>						
Access/egress	-0.352 (-30.74)	-0.375 (-27.38)	-0.329 (-18.24)	1.85	1.74	2.02
Waiting time at transfers	-0.034 (-13.43)	-0.036 (-15.02)	-0.030 (-6.72)	0.18	0.17	0.18
Walking time at transfers	-0.087 (-7.45)	-0.083 (-5.48)	-0.098 (-5.27)	0.46	0.38	0.60
<b>Other components</b>						
Transfer penalty	-1.750 (-30.71)	-1.740 (-24.22)	-1.800 (-19.65)	9.21	8.06	11.04
<b>Number of observations</b>	5,121	2,667	2,454			
<b>Null log-likelihood</b>	-24,722	-13,063	-11,659			
<b>Final log-likelihood</b>	-12,592	-6,229	-6,327			
<b>Adjusted rho square</b>	0.490	0.523	0.457			

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### 3.2 Elaborate specification

Taking outset in the base specification, various alternative specifications including additional variables were estimated. This process led to the model specification and parameters presented in Table 3. The log-likelihood of this specification is significantly better than the base specification (-12,075 vs. -12,592), and all parameters are significant and with the expected sign. Looking at the rates of substitution, the results show that waiting time at the first stop is preferred compared to bus in-vehicle time. However, this is most likely due to the inclusion of the highest headway of the trip, because many trips only have one leg and the waiting time at the first stop depends on the headway and service type (SB/FB) of the first leg. When considering the highest headway of the trip, the reduction of one minute in bus in-vehicle time is equivalent to a reduction of the headway of 7 minutes. This headway should also be reflected in a lower waiting time at the first stop, so the reduction in utility would be greater than just the contribution from the headway parameter.

The distinction between waiting for a FB vs. SB service gives significantly different parameter estimates as waiting for FB services is four times worse than waiting for SB services. It is important to note, that the interval covered by FB waiting time is between 0 to 14 minutes, while waiting times for SB services extend into more than an hour. Moreover, tests using piecewise linear parameters and Box-Cox transformations for the split waiting times showed that waiting time for FB services is in all cases worse than waiting for SB services. The difference in the parameter estimates could be due to the higher uncertainty of waiting time for a FB service, as the passenger does not know when the next service will depart exactly. For SB services the waiting time is more certain, as it is given from the explicit timetable, and this could influence the passenger's route choice because they are more certain on when they will arrive at their destination.

The specification also includes a dummy describing whether the route includes a FB service. The parameter estimate of 0.545 indicates that passengers prefer routes with FB services compared routes without FB services. The positive parameter could be explained by the fact, that routes including FB services are typically high frequent routes, which gives a security for the passenger to not be significantly delayed if the first departure is missed.

Table 3 - Model estimates (robust t-test) for model with elaborate specification with linear parameters and rates of substitution scaled to bus in-vehicle time

	Model estimates			Rates of substitution (to bus IVT)		
	Trip purpose			Trip purpose		
Parameter	All	Work	Leisure	All	Work	Leisure
<b>In-vehicle times</b>						
Bus	-0.180 (-29.84)	-0.205 (-24.67)	-0.154 (-19.1)	1.00	1.00	1.00
Metro	-0.096 (-9.29)	-0.117 (-7.92)	-0.072 (-5.23)	0.53	0.57	0.47
S-train	-0.152 (-22.00)	-0.176 (-16.77)	-0.124 (-14.53)	0.84	0.86	0.81
Regional train	-0.209 (-19.83)	-0.221 (-16.00)	-0.196 (-10.30)	1.16	1.08	1.27
Local train	-0.156 (-10.45)	-0.193 (-9.90)	-0.126 (-4.40)	0.87	0.94	0.82
<b>Other time components</b>						
Access/egress	-0.377 (-29.79)	-0.405 (-26.48)	-0.351 (-17.83)	2.09	1.98	2.28
Headway	-0.026 (-8.61)	-0.028 (-6.39)	-0.025 (-5.80)	0.14	0.14	0.16
Waiting time at first stop	-0.100 (-5.31)	-0.118 (-5.05)	-0.085 (-2.79)	0.56	0.58	0.55
Transfer waiting time for SB service	-0.027 (-11.43)	-0.029 (-12.92)	-0.023 (-5.64)	0.15	0.14	0.15
Transfer waiting time for FB service	-0.116 (-12.36)	-0.128 (-9.35)	-0.105 (-8.16)	0.64	0.62	0.68
Walking time at transfers	-0.098 (-8.18)	-0.095 (-6.00)	-0.106 (-5.74)	0.54	0.46	0.69
<b>Other components</b>						
Transfer penalty	-1.820 (-29.68)	-1.830 (-23.54)	-1.850 (-18.98)	10.11	8.93	12.01
Trip include FB service	0.545 (8.17)	0.576 (5.75)	0.521 (5.75)	-3.03	-2.81	-3.38
<b>Number of observations</b>	5,121	2,667	2,454			
<b>Null log-likelihood</b>	-24,722	-13,063	-11,659			
<b>Final log-likelihood</b>	-12,075	-5,944	-6,089			
<b>Adjusted rho square</b>	0.511	0.544	0.477			

### 3.3 Elaborate specification with Box-Cox transformations of in-vehicle time

As shown in the previous subsections passengers have different preferences for the individual sub modes. To test whether the marginal utility of each of the variables change depending on time spent in the vehicles, a specification identical to the one described in section 3.2 is estimated, however using Box-Cox transformations of all variables related to in-vehicle times. The resulting parameters of the estimation on the full dataset are for all non in-vehicle time parameters almost identical to the elaborate model presented in Table 3 and all parameters remain significant. The log-likelihood is improved from -12,075 in the linear elaborate model to -11,901 in the elaborate model with Box-Cox transformations. Figure 8 shows how the marginal utility decreases over time for regional train, while for S-train and metro the marginal utility increases. The high marginal increase in utility for in-vehicle time in metro ( $\lambda = 2.02$ ) could be a result of the few seats in the metro and thereby simulating a standing penalty, which is mostly in place for longer trips of more than 10 minutes. For the in-vehicle time in S-trains the marginal increase is less than for metro ( $\lambda = 1.47$ ), but with no tables at the seats and a high load on the trains in peak hours, the marginal increase for longer in-vehicle times seem behaviourally correct. The marginal decrease in utility for regional train ( $\lambda = 0.70$ ) is as expected, as passengers in regional trains can use the time more efficient with tables at the seats and a general higher comfort level. Figure 8 only shows the utility on the central 95% of the observations, but from the figure it is clear, that for trips longer than an hour, the regional train is preferred. In-vehicle time for bus is almost linear ( $\lambda = 0.95$ ) and could be explained by a high disutility for shorter trips, where a seat might not be available, and a lower disutility for longer trips, where a seat will often become available on the bus at some point.

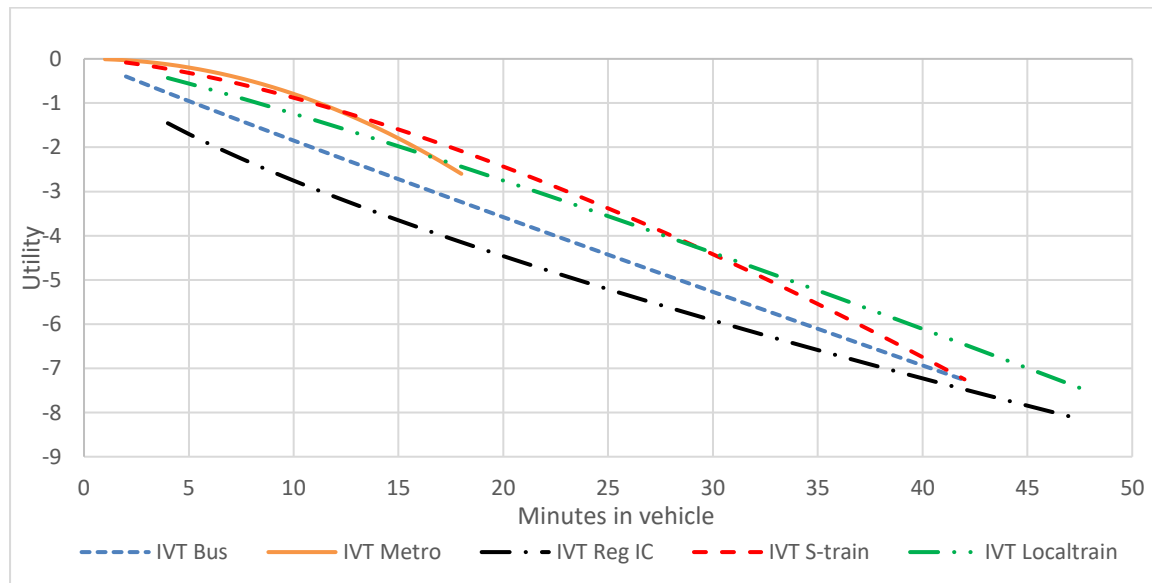


Figure 8 - Utility of in-vehicle time for model with elaborate specification with Box-Cox transformation of the variables related to in-vehicle time.

Curves only shown for the central 95% of observations for each variable (zeros excluded)

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## 4 Discussion and conclusion

This section discusses and concludes on the findings presented in section 3 and how these findings can be used for further improving public transport assignment models.

### 4.1 Dealing with departure time choice within route choice models

An important aspect of public transport route choice is when the passenger can depart from the origin, and in most cases even more important when the passenger can arrive to the destination. For FB networks (and FB assignment models) this aspect is not as important, as departures are possible at all times. In SB networks (and SB assignment) the possible departure and arrival times are crucial, because passengers want to time their arrival to for example work or leisure activities. As the departure times are discrete in time, it might be, that passengers need to arrive earlier or later than the preferred arrival time. This time between preferred and actual arrival time is called hidden waiting time. Departure time choice is a well-established research field (see Thorhauge (2015, chap. 1) for a comprehensive list of previous studies), and for this study it would be relevant to include, as many alternatives have a departure time which differs significantly (more than 10 minutes) from the reported departure time. It has not been possible to estimate a parameter for this hidden waiting time, because the observed route will always be the best on this variable, making it impossible to estimate the parameter. Future research will focus on how to deal with this issue by for example fixing the parameter according to the total in-vehicle time based on stated preference surveys.

### 4.2 Implications of findings for public transport traffic assignment models

The findings of this paper can be used to model the route choice of public transport users in traffic assignment models at a higher level of detail. The difference in preferences for SB and FB services underlines the need to focus on creating an assignment model that can take both types of services into consideration. Modellers today are faced with only the choice between either a FB or SB assignment model to model a certain area, but if the model could represent realistically both FB and SB services there might be a potential benefit in the ability to better replicate passenger choices in public transport.

### 4.3 Conclusion

The estimations using real-life observed route choice data collected in a complex multi-modal public transport network have provided an insight into the impact of several factors that affect passengers' route choice in mixed SB and FB public transport systems. Findings related to preferences for waiting time for FB and SB services show that passengers prefer to be more certain about their waiting time. On the other hand, the positive parameter for whether a route includes a FB service shows that passengers prefer highly frequent services, which FB services typically are when compared to SB services. This indicates that passengers' value having many possible departures, which is in line with the preference for routes with lower headways. Finally, the paper showed, that the preferences for in-vehicle time in sub modes change according to how much time is spent in a specific sub mode.

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